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Wind tunnel and numerical modeling of atmospheric boundary layer flow over Bolund Island

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Abstract

The paper presents a comparison between the experimental and numerical results on the flow around a Bolund Island 1:705 scale model. A boundary layer wind tunnel with expansion stage was used for experimental modelling [9]. Velocity fields were determined using Constant Temperature Anemometry (CTA) and Particle image Velocimetry (PIV) measurements. Unsteady numerical simulations were performed using a Reynolds Average Navier Stokes (RANS) turbulence model adapted to atmospheric boundary layer flows [6] which was implemented in the ANSYS FLUENT expert software.
At the beginning, the wind tunnel with expansion stage was explored and measurements were performed to determine the flow characteristics in the experimental vein. Data from CTA measurements in the median longitudinal plane, in eleven sections located at different distances from the expansion stage were used to determine mean velocity ant turbulence intensity profiles. Comparison with real data from the Bolund experiment showed a good agreement with the wind tunnel measurements.
The experimental 1:705 scale model of the Bolund Island was manufactured on a CNC machine using the topographical data provided by the Risø DTU team from the Bolund experiment. Same data was used to build the mesh which virtually replicates the model placed in the experimental vein of the wind tunnel.
PIV measurements were performed in order to determine the velocity, turbulence intensity and vorticity contours in a vertical reference plane and then compared to the URANS numerical simulation results.

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1. Introduction

In this article we present a comparison between the experimental measurements on the flow around the Bolund island 1:705 scale model placed in the experimental vein of the TASL-3 boundary layer wind tunnel and the numerical simulation results in a virtual wind tunnel that reproduced the experimental set-up geometry and boundary conditions.

The Bolund experiment [1] is a field campaign that provides a unique dataset for validating models designed for flow around complex terrain. The experiment was conducted from December 2007 to February 2008 on the Bolund Island located 1 km north of Risø DTU National Laboratory for Sustainable Energy from Technical University of Denmark (DTU) [1].

Bolund Island is a 12 m high, 130 m long and a 75 m wide island located just north of Risø DTU (see Figure 1). The geometrical shape of the hill consists of properties that characterize a complex terrain. Properties like a well-exposed almost vertical upstream escarpment, a sharp change in surface roughness with the wind passing from water to grass and a highly complex three-dimensional geometry make the Bolund hill a challenging test case for any numerical flow solver [1].

During the campaign, data about the velocity and the high frequency turbulence were simultaneously collected from 35 anemometers distributed over 10 masts with a total of 23 sonics, 12 cups and 2 lidars used [1].

Fig.1. Overview of Bolund from Google Earth

The predominant wind direction during the experiment was south southwest (see Figure 2). With winds from West there is a long fetch of sea of approximately 7 km (line B 270˚), while the fetch with the wind from West Southwest (line A 239˚) is about 4 km [1].

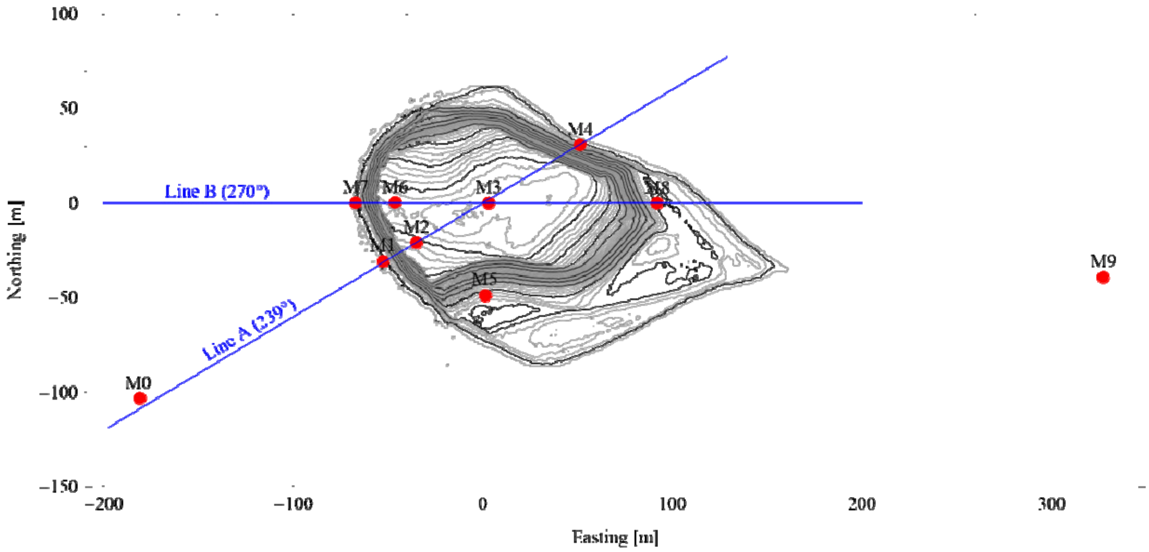


Fig.2. The Bolund orography and the mast positions along line A and B. The two lines cross the centerpoint of Bolund (CP) that is located close to Mast M3 [1].

2. The boundary layer wind tunnel with expansion stage exploration

In order to obtain velocity and turbulence intensity profiles similar to the flow in the atmospheric boundary layer, at the "Constantin Iamandi" Aerodynamics and Wind Engineering Laboratory from the Hydraulic and Environmental Protection Department from Technical University of Civil Engineering Bucharest, a specialized wind tunnel, different from classical ones, was used. This wind tunnel, called the staple wind tunnel (with expansion stage) was developed after an original idea of Professor Constantin Iamandi (see Figure 3).

2.1. Tables

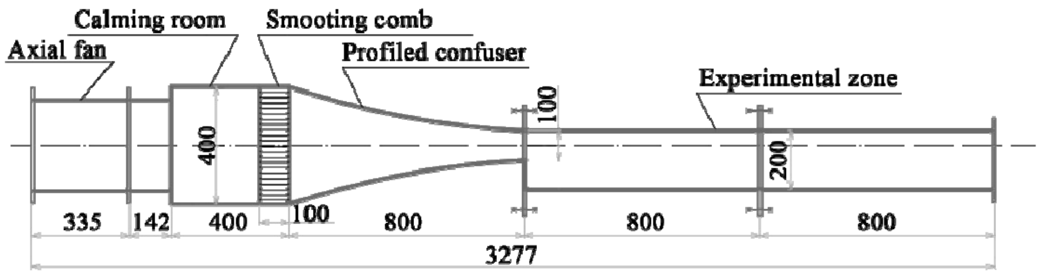


Fig.3. Wind tunnel with expansion stage constructive system [9].

The existence of a discontinuity surface in the rectangular flow section shaped as an asymmetric abrupt expansion in the lower section, causes the flow to separate. Although, the flow is three-dimensional, in each vertical, longitudinal plane, the flow may be seen as a two-dimensional separated flow. The whole process of flow separation is the whole complex phenomenon which implies detachment, recirculation, free friction flow and reattachment of the fluid stream. The separation occurs when the fluid is passing the upper edge of the expansion stage and is accompanied by large variations in speed and pressure in the separation zone [2]. In Figure 4, the flow spectrum is the wind tunnel with expansion stage is visualized using the tuft flow visualization.

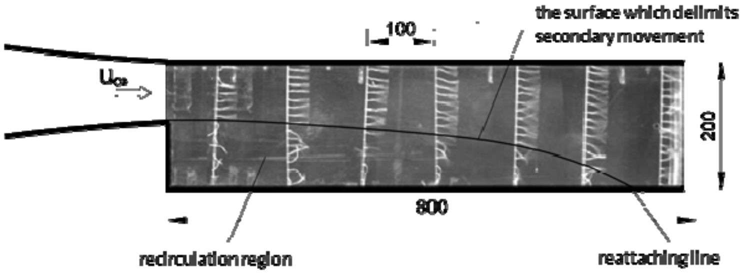


Fig.4. Tuft flow visualization in the wind tunnel experimental vein highlighting the area of separation and recirculation of the air stream downstream the expansion step.

For the measurements, we used three methods known in wind engineering for air velocity measurement, i.e. Pitôt-Prandtl probe, constant temperature anemometer (CTA) [7] and Particle Image Velocimetry (PIV) [8].

2.2. Exploration results

Measurements were made using Pitôt-Prandtl probe and hot wire anemometer into the experimental vein of the wind tunnel with expansion stage into different sections of the tunnel. The Pitôt-Prandtl probe was used in these experimental tests in order to measure the reference velocity for the subsequent hot wire anemometer measurement with. The Pitôt-Prandtl probe was connected to a piezoelectric pressure transducer and, using a digital multimeter, we determined the local mean velocity.

Then, CTA measurements were performed to determine the flow characteristics in the experimental vein of the wind tunnel with expansion stage, using a 1D 55P5 Dantec probe. These measurements were made in the median longitudinal plane, in eleven sections located at different distances measured along the flow, starting from the expansion stage (0 cm, 10 cm, 20 cm, 30 cm, 40 cm, 50 cm, 57.5 cm, 80 cm, 100 cm, 120 cm and 137.5 cm). The vertical distance between two measurements in the same section was equal to 5 mm.

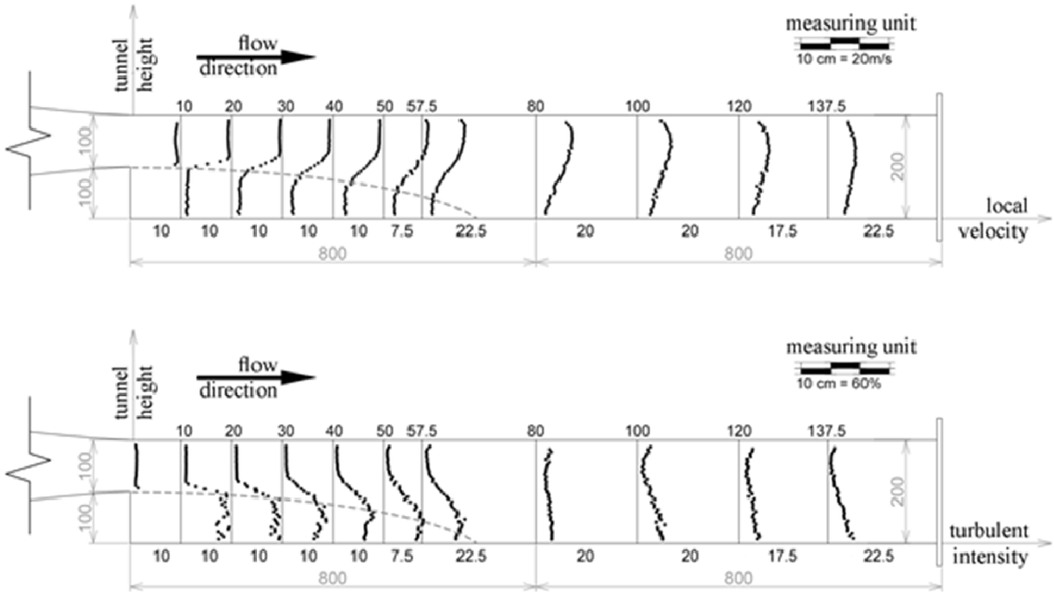


Fig.5. Local axial velocity and turbulent intensity distribution in different sections in experimental vein of the wind tunnel with expansion stage.

The last three sections of the wind tunnel experimental vein, is the active measurement section where we placed the Bolund Island model. Here we determined the theoretical curve which successfully approximates a logarithmic law profile for the velocity distribution valid up to a dimensionless height of 0.175 (with respect to the wind tunnel height), i.e. 35 mm in the tunnel. The 35 mm height in the wind tunnel corresponds to the height of 25 m in full scale, which is the reference altitude for the measurements of high air movement over the Bolund Island.

To determine the theoretical curve we have performed a linear regression on the known data such as average local velocity and height of the tunnel. Then, we determined the roughness for each measuring section. For each section, we introduced the roughness in the logarithmic law formula and, knowing the average local velocity, we computed the friction velocity for each measuring point which was then averaged on section.

The PIV measurements were performed only in the area surrounding the 1200 section, in the vertical median plane of the wind tunnel.

In Figure 6 are presented the wind tunnel measured dimensionless velocity profiles in the 1200 mm section, approximated by the logarithmic law and the same profile determined at full scale, upwind the Bolund Island (mast M0, wind direction 270o). One may observe a very good agreement between the full scale and wind tunnel measurements. The reference velocity on the model was computed at a height of 35 mm in the wind tunnel for the CTA and PIV measurements and on a height of 25 m for the full scale measurements.

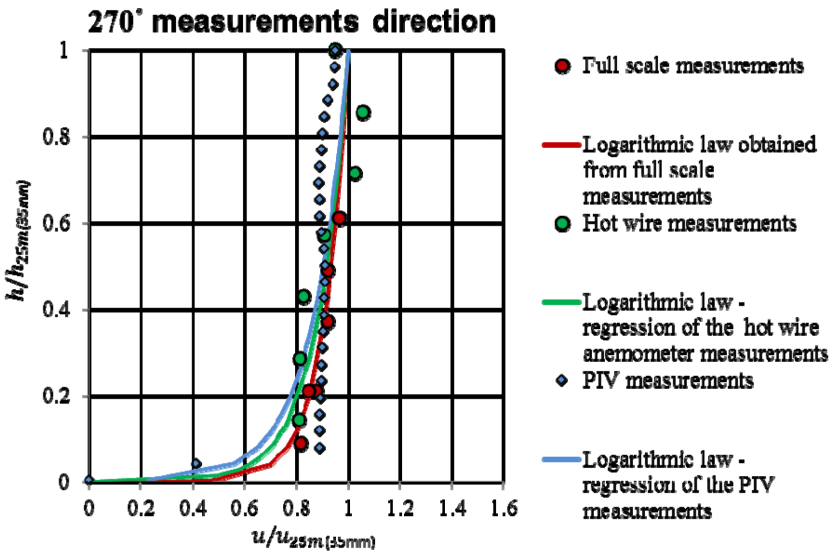


Fig.6. Measured velocity profiles in the 1200 mm wind tunnel section compared with the full scale data.

3. Experimental tests on the flow around the Bolund Island 1:705 scale model

In these testing we used the PIV system. It has a big advantage because it can deliver full information on a measuring field for the distribution of absolute average velocity, vorticity and turbulence intensity.

3.1. Physical model of the Bolund island

The experimental 1:705 scale model of the Bolund Island was manufactured from Medium Density Fiberboard (MDF), on a CNC machine using the topographical data provided by the Risø DTU team from the Bolund experiment.

The model scale was chosen so that the island will not obstruct more than 5% of the wind tunnel cross-section in order to avoid the blocking phenomenon and influence of the walls delimiting the experimental area.

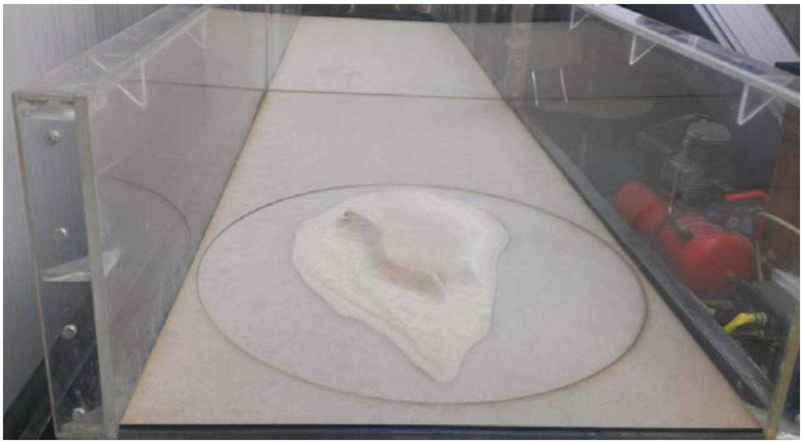


Fig.7. The Bolund Island in the wind tunnel with expansion stage experimental vein.

3.2. The similitude for the physical modeling of the phenomenon of wind interaction with the Bolund Island

The modeling problem was solved in the sense that the models with sharp edges, such as 1:705 Bolund Island scale model, tested in wind direction from the coast with a sharp edge (direction of 270˚) (Fig. 8.1 and Fig. 8.2), due to changes in the structure of movement in the boundary layer of the model and because of the different nature of the movement in the wake of downstream model, it was found that, above a certain value, relatively small, of the Reynolds number, as the Reynolds number is attached to the flow over the model, the nature of motion in the turbulent boundary layer and in the wake remains unchanged at increased wind velocity and the flow structure around the island model remains unchanged. Therefore, although the condition of similarity Re=idem could not be met, the phenomenon of the model island located in the wind tunnel experimental vein was in the automodelling range in terms of Reynolds number. This was verified as the dimensionless average velocity profiles from nature and wind tunnel are practically overlapped.

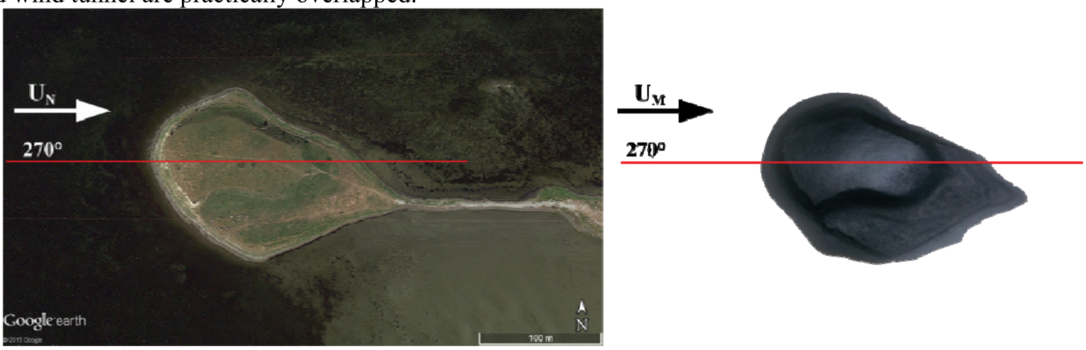
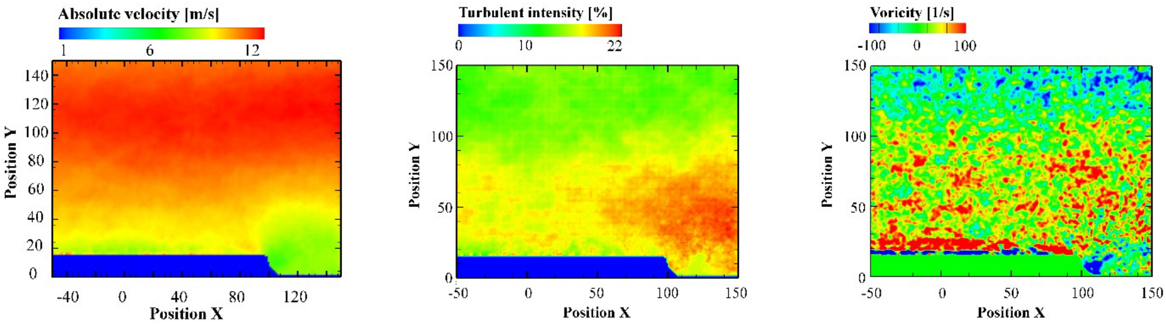
a)  b)

Fig.8. – a) The Bolund island at full scale (N) and the wind directions where full scale measurements were made UN (270° direction).

b) Bolund island model (M) at the length scale of S_l=1/705 and the wind direction in the wind tunnel UM (270° direction).

3.3. Results of the experimental tests

The results were reconstructed from 120 successive measurements recorded using an ILA PIV system, at a 4Hz frequency between two consecutive double laser pulses. The Laser pulses were equal to 100 µs and the exposure time of the camera was equal to 70 µs for each pulse. Seeding of the flow was achieved using olive oil as a seeding material. We investigated a narrow field, in the vertical plane of the flow, containing the 270^o line, near the sharp edge of the island, with a length of 150 mm (on the model scale).Distributions of average velocity, turbulence intensity and vorticity resulted from the measurements are presented in Figure 9 a), 9.b) and 9.c), respectively.



a) b) c)

Fig.9. a) Average velocity distribution over the Bolund island model; b) Turbulent intensity distribution over the Bolund island model. c)` Vorticity distribution over the Bolund island model.

4. Numerical simulations on the flow around the virtual Bolund island 1:705 scale model

Based on the physical model set-up of the Bolund island, we performed an unsteady numerical simulation that reproduces the air flow around the island model placed in the experimental vein of the wind tunnel.

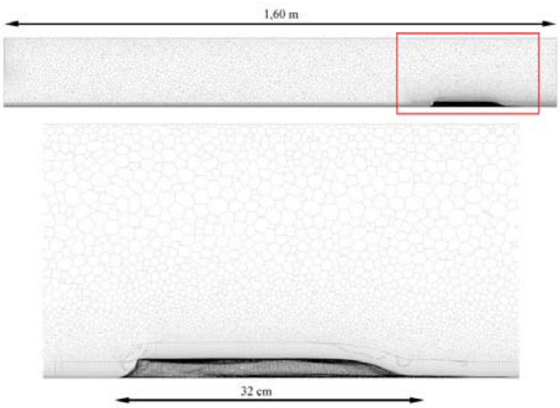


Fig.10. Bolund Island mesh reproducing the wind tunnel set-up On the bottom, the location of the island is magnified.

The mesh is mixed, made from hex and polyhedral cells, converted from a mixed hex-tet grid. The number of cells is equal to 4378270. The initial mixed tet-hex mesh had 8931178 cells. The grid was converted to polyhedra in order to minimize the computational effort and also to improve the quality of the final numerical solution [5]. In the boundary layer around the island and the floor of the wind tunnel, 24 layers of hex cells distributed along the normal to solid surfaces using an exponential law were constructed in order to properly resolve the sharp variations of flow parameters in this region and also to ensure a proper y+ distribution for the chosen turbulence model.

For the turbulence model we used a k-ε variation proved to be robust and give better results when simulating the flow around complex topographic shapes or other characteristics present in the simulated atmospheric boundary layer [4]. More details about k-e Monin Obukhov turbulence model are presented in [6].

At the inlet in the simulation domain, velocity, kinetic energy (k) and turbulent dissipation rate (e) profiles determined using the velocity and turbulence intensity profiles measured using the CTA in the wind tunnel were assigned. The unsteady simulations were performed after an initial flow field was obtained from a steady state simulation. The time step was equal to 1e-5 seconds, the total flow time being equal to 0.11 seconds.

Local and mean time velocity field of the flow over the island model were determined (Figure 11) aiming to obtain velocity distributions along the fluid lines located at a height of 7.09 mm and 12.76 mm, respectively above the model, corresponding to the fluid lines located at the height of 5 m and 9 m above the contour of the full scale island.

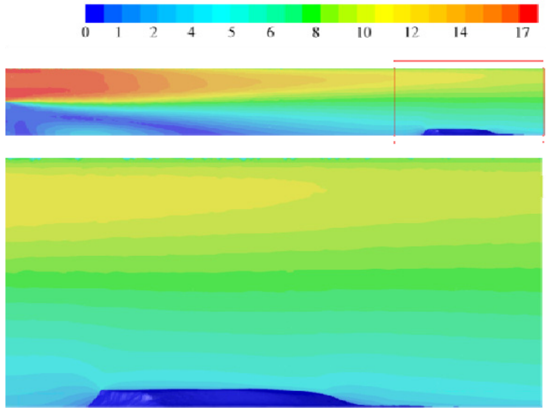


Fig.11. The average in time of local velocity field for numerical tests in the wind tunnel, being highlighted Bolund island area.

The results of the numerical tests of the distributions of dimensionless velocity along the fluid lines of 7.09 mm and 12.76 mm are shown in Figure 12, in comparison to the dimensionless velocity distributions to the same height results from the experimental tests performed in the wind tunnel using the PIV system. The numerical simulation is correctly predicting the increase of the velocity in the zone near the vertical wall of the island. Upwind the model (mast M7), the numerical simulation overestimates the velocity decrease, while on the upper part of the island (mast M3), the turbulence model returns slightly higher values of the velocity when compared to the experimental measurements.

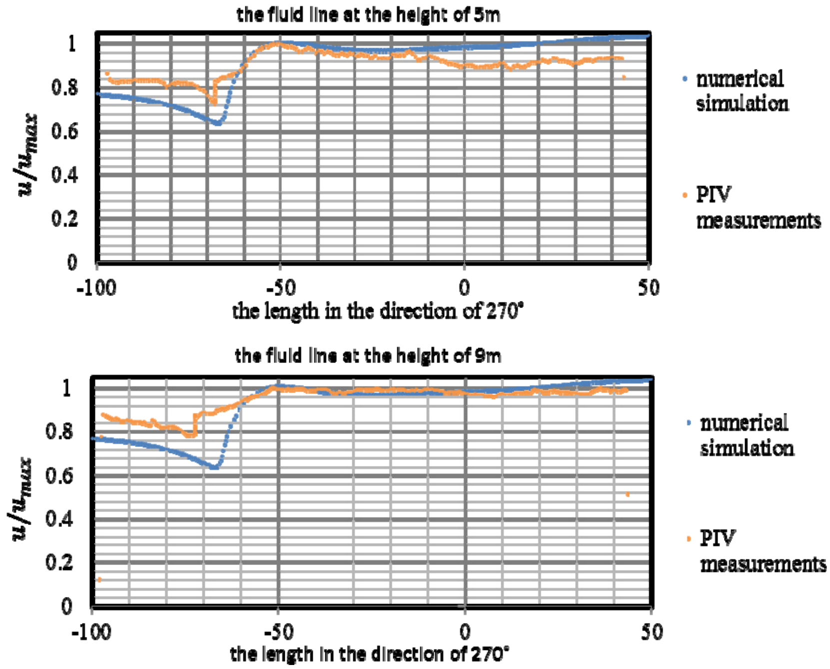


Fig.12. The chart comparing the dimensionless velocity distributions along the fluid lines located at 7.09 mm and 12.76 mm above the Bolund Island 1:705 scale model obtained from PIV measurements and numerical simulations.

5. Conclusions

Experimental and numerical results on the flow around a Bolund Island 1:705 scale model were performed.

In order to assess the flow field (velocity ant turbulence intensity profiles) in the aerodynamic wind tunnel with expansion stage, we performed CTA measurements in 11 vertical sections placed in a median vertical plane along the experimental vein and PIV measurements in the active area of the experimental zone. A very good agreement between the full scale and wind tunnel measurements for the velocity profile was determined.

Considering the characteristics of the flow in the experimental vein and assuming a maximum obstruction of the cross-sectional area of the experimental vein equal to 5%, a 1:705 scale model of the Bolund Island was manufactured on a CNC machine.

PIV measurements were performed on the flow around the Bolund Island 1:705 scale model. The flow was in the automodelling range in terms of Reynolds number as the dimensionless average velocity profiles from nature and wind tunnel were practically overlapped.

Unsteady numerical simulations on the flow around the virtual Bolund Island 1:705 scale model were performed which reproduced the wind tunnel experimental set-up.

Although the results are not overlapping in the whole fluid domain, from the analysis of experimental and numerical results of air flow at model scale results in a good match of numerical results with experimental results in the wind tunnel, which is an incentive to achieve a numeric wind tunnel.

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